Right-handed Neutrino Magnetic Moments

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Outline

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2. Dimension 5 Effective Lagrangian with ν_R
3. Astrophysical and Cosmological Considerations
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Neutrinos have masses

- The last 20 years have been very exciting in neutrino physics, with the confirmation that neutrinos have masses, and that mass and flavor eigenstates are mixed.
- Yet we still face some unanswered questions, such as which is the true character of neutrino masses –Dirac or Majorana– and what are the values of the masses.
- All we have up to date are upper bounds, both direct, as those coming from searches in $^3\mathrm{H}$ β-decay, and indirect, as the ones obtained from structure formation in cosmology.
- Essentially we can state that $m_\nu \lesssim 1\,\mathrm{eV}$ and probably $m_\nu \lesssim 0.05\,\mathrm{eV}$.

Neutrino mass models

- Plain Dirac neutrino masses
- Type I seesaw mechanism (very natural)
- Triplet of scalars or fermions (type II and III seesaw)
- Inverse see-saw
- Radiative neutrino masses (Zee and Zee-Babu models)
- SUSY models without R-parity
- ν masses from extra dimensions
- ν masses from Little Higgs models
- …

A lot of possibilities.
Can we perform a model-independent analysis of ν masses?

Effective field theory approach

Assumptions:

- The SM is a low-energy approximation of a more complete theory.
- The only light particles ($m \lesssim 250\,\mathrm{GeV}$) are those of the SM.

Then we can write

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_5 + \mathscr{L}_6 + \cdots$$

$$\mathscr{L}_{\mathrm{SM}} = i\bar{\ell}\,\not{D}\,\ell + i\overline{e_R}\,\not{D}\,e_R - (\bar{\ell}\,Y_e e_L\,\phi + \mathrm{h.c.}) + \cdots$$

$\mathscr{L}_5$, $\mathscr{L}_6$, ... contain dim 5, dim 6 ... operators built with SM fields and symmetries.
Their effects are suppressed by $1/\Lambda_{NP}$, $1/\Lambda_{NP}^2$ ..., being Λ_{NP} the scale of new physics.

Weinberg operator

As soon as at dimension 5 there appears the operator

$$\mathscr{L}_5 = \frac{1}{\Lambda_{\rm NP}} \left(\bar{\tilde{\ell}}\phi\right) \eta \left(\tilde{\phi}^{\dagger}\ell\right)$$

which after SSB gives rise to Majorana neutrino masses

$$m_\nu \sim \frac{v^2}{\Lambda_{\rm NP}} \ll v\,, \quad \text{if} \qquad \Lambda_{\rm NP} \gg v$$

- Thus the masses are naturally small.
- However, this operator parametrizes only Majorana masses.
- To account for (possible) Dirac masses, we need right-handed degrees of freedom.

Adding ν_R

The most general mass-generating terms involving SM fields and ν_R are

$$\mathscr{L}_{\text{mass}} = -\bar{\ell} Y_e \phi e_R - \bar{\ell} Y_\nu \tilde{\phi} \nu_R - \frac{1}{2} \overline{\nu_R^c} M_R \nu_R + \text{h.c.}$$

which lead, after SSB, to the neutrino mass matrix

$$\mathscr{L}_{\nu M} = -\frac{1}{2} \left(\bar{\nu}_L, \overline{\nu_R^c} \right) \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

- We consider also the M_R term for generality reasons, and also because we've got no reason to drop it. If we want pure Dirac masses we can always do $M_R = 0$.
- Besides, with that term we can do seesaw to account for the smallness of the ν masses.

Dimension 5 Effective Lagrangian with ν_R

Consider the ν_R among the light degrees of freedom:

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\nu_{\mathrm{R}}} + \mathscr{L}_5 + \cdots$$

$$\mathscr{L}_{\nu_R} = i\overline{\nu_R}\partial\!\!\!/\, \nu_R - \left(\frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \mathrm{h.c.}\right) - \left(\bar{\ell} Y_\nu \nu_R \tilde{\phi} + \mathrm{h.c.}\right)$$

If we repeat the same program, this time we obtain three dimension 5 effective operators

$$\mathscr{L}_\chi = \left(\bar{\tilde{\ell}}\phi\right) \chi \left(\tilde{\phi}^\dagger \ell\right) + \mathrm{h.c.}$$

$$\mathscr{L}_5 = \mathscr{L}_\chi + \mathscr{L}_\zeta + \mathscr{L}_\xi \qquad \mathscr{L}_\xi = -\left(\phi^\dagger\phi\right) \overline{\nu_R^c} \xi \nu_R + \mathrm{h.c.}$$

$$\mathscr{L}_\zeta = \overline{\nu_R^c} \zeta \sigma^{\mu\nu} \nu_R B_{\mu\nu} + \mathrm{h.c.}$$

These three are the lowest-order operators in $1/\Lambda_{NP}$.

Mass-base Lagrangian

In order to make calculations, we should write the operators in terms of the mass eigenfields. To do this, we will assume seesaw between the ν_L and the ν_R:

$$\begin{aligned} \nu_L &= P_L\,(U_\nu \nu + \varepsilon U_N N + \cdots) \\ \nu_R &= P_R \left(U_N N - \varepsilon^T U_\nu \nu + \cdots \right) \end{aligned}$$

$$\varepsilon \approx M_D M_R^{-1}\,, \qquad |\varepsilon_{ij}| \lesssim \sqrt{\frac{m_\nu}{m_N}}$$

$$\begin{aligned} \mathscr{L}_\zeta &= \left(\overline{N} U_N^T - \overline{\nu} U_\nu^T \varepsilon \right) \sigma^{\mu\nu} \left(\zeta P_R + \zeta^\dagger P_L \right) \left(U_N N - \varepsilon^T U_\nu \nu \right) \times \\ &\quad \times \left(c_W F_{\mu\nu} - s_W Z_{\mu\nu} \right) \end{aligned}$$

Astrophysical effects

The electroweak moment interaction gives rise to transition magnetic moments between all species of N's and ν's

$$\mathscr{L}_{\rm magmo} = \left(\overline{N} - \overline{\nu}\varepsilon\right) \sigma^{\mu\nu} \left(\zeta P_R + \zeta^\dagger P_L\right) \left(N - \varepsilon^T \nu\right) c_W F_{\mu\nu}$$

These interactions enable the production of N's and ν's within astrophysical objects. As they are weakly-interacting particles, they'll be able to escape freely from the object, thus contributing to its cooling.
These cooling mechanisms are well constrained. For our interaction we found that the best limits come from

- Plasmon decays in red giants (for $m_N \lesssim 10\,\text{keV}$)
- $\gamma + \nu \to N$ in supernovae (for $m_N \lesssim 30\,\text{MeV}$)

Plasmon decay in red giants

In a plasma photons have massive excitations called plasmons. If $N_1 N_2$ have magnetic moments, and are light enough, plasmons could decay into $N_1 N_2$ and produce an extra cooling mechanism.

We find (ω_P plasma frequency, ω plasmon energy)

$$\Gamma(\text{plasmon} \to NN) = \frac{\mu_{\text{eff}}^2}{24\pi} \frac{\omega_P^4}{\omega}$$

$$\mu_{\text{eff}}^2 = 16 c_{\text{W}}^2 \sum_{\text{all}} \left|\zeta_{ij}\right|^2 f_Z(\omega_P, m_i, m_j)\,,$$

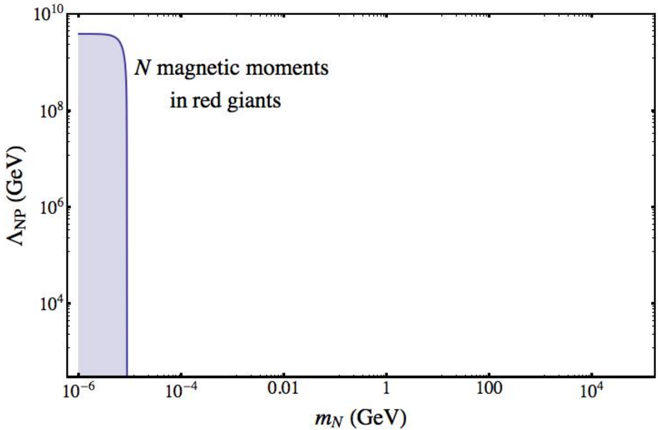
The observational limits from red giant stars cooling imply

$$\mu_{\text{eff}} < 3 \times 10^{-12} \mu_B\,,$$

Then for $m_i, m_j \ll \omega_P \simeq 8.6\,\text{keV}$

$$|\zeta_{ij}| < 8.5 \times 10^{-13} \mu_B; \quad \text{and} \quad \Lambda_{NP} \gtrsim 4 \times 10^6\,\text{TeV}$$

First bound: Red Giants



$\gamma + \nu \to N$ in supernovae

In the SN core ν's are trapped while, in principle, N escape freely.

Any process transforming ν's into N's can potentially destabilize the standard SN cooling.

Therefore, $\gamma + \nu \to N$, induced by our ν-N transition magnetic moment, will be strongly bounded:

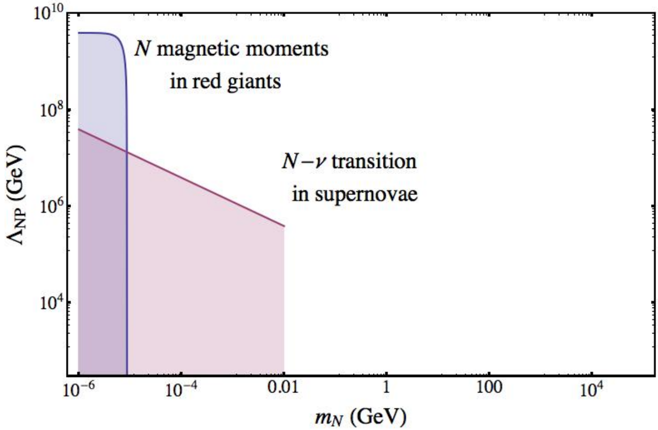
Using that the coupling for this process is suppressed $\sim \zeta\varepsilon \sim \left(\sqrt{m_\nu/m_N}\right)/\Lambda_{NP}$ one finds

$$\Lambda_{NP} \gtrsim 4 \times 10^6 \times \sqrt{m_\nu/m_N}\,\mathrm{TeV}\,, \quad \text{if} \qquad m_N < 30\,\mathrm{MeV}$$

These limits are interesting in the region $10\,\mathrm{keV} < m_N < 30\,\mathrm{MeV}$, where red giant bounds do not apply.

But depend strongly on the assumptions on ε.

Second bound: Supernovae



Collider effects

Right-handed neutrinos have no EW interactions.
The only interaction with SM particles is the Yukawa coupling, which must be very small in type I seesaw scenarios if heavy neutrinos are light enough to be produced at colliders:
ν_R difficult to produce at colliders
The new right-handed neutrino interactions can give access to ν_R properties:

- The magnetic moment interaction can enhance ν_R production at colliders (Z and γ exchange at e^+e^- colliders and Drell-Yan at hadron colliders)
- It can also affect the way they could be detected.
- The $\mathscr{L}_\xi$ can affect dramatically Higgs boson decays.

For simplicity we will only consider the two lighter N's, N_2 and N_1 with $m_2 > m_1$.

Invisible Z Decay Width

If N_1, N_2 are produced but undetected additional contribution to $Z \to$ invisible

$$\Gamma_{inv} = 3\Gamma^{SM}_{\bar{\nu}\nu} + \Gamma(Z \to N_1 N_2) = 499.0 \pm 1.4\,\mathrm{MeV}$$

then

$$\Gamma(Z \to N_1 N_2) = \Gamma_{inv} - 3\left(\frac{\Gamma_{\bar{\nu}\nu}}{\Gamma_{\bar{\ell}\ell}}\right)^{SM} \Gamma_{\bar{\ell}\ell} \simeq -2.6 \pm 1.5\,\mathrm{MeV}$$

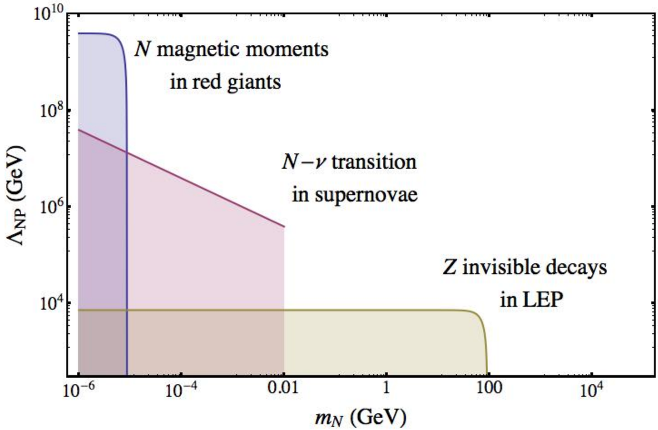
gives

$$\Gamma(Z \to N_1 N_2) < 0.72\,\mathrm{MeV} \qquad 90\%\,\mathrm{CL}\,,$$

in terms of

$$\Lambda_{NP} = \frac{1}{|\zeta_{12}|} > 7\sqrt{f_Z(m_Z, m_1, m_2)}\ \mathrm{TeV}$$

Third bound: LEP



N_1, N_2 production at the LHC

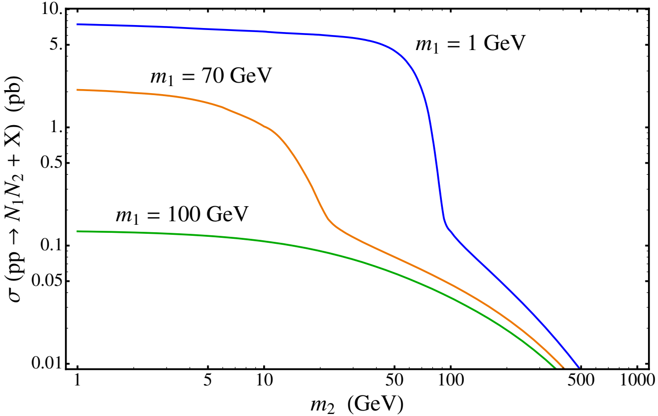
Heavy neutrinos will be produced at the LHC through the Drell-Yan process.
Computed in terms of the the partonic cross sections

$$d\sigma(pp \to N_1 N_2 + X) =$$

$$\sum_q \int_0^1 dx_1 \int_0^1 dx_2 \left(f_q(x_1, \hat{s}) f_{\bar{q}}(x_2, \hat{s}) + (q \leftrightarrow \bar{q})\right) d\hat{\sigma}(q\bar{q} \to N_1 N_2, \hat{s})$$

$\hat{s} = x_1 x_2 s$ the partonic center of mass invariant square mass
$\hat{\sigma}(q\bar{q} \to N_1 N_2, \hat{s})$ the partonic cross section
$f_q(x_1, \hat{s})$, $f_{\bar{q}}(x_2, \hat{s})$ the parton distribution functions of the proton.

$\Lambda_{NP} = 10\,\text{TeV}$ and $\sqrt{s} = 14\,\text{TeV}$

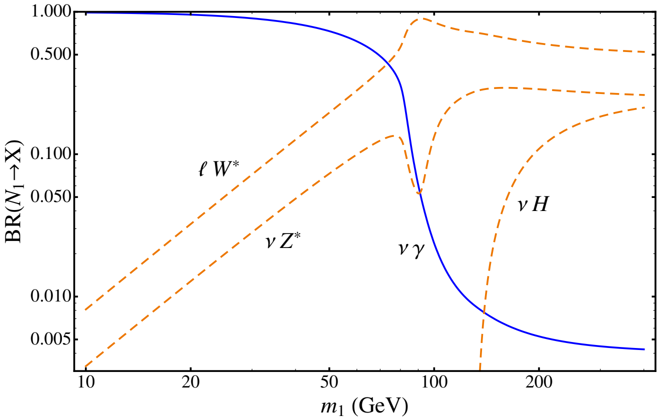


Cross sections above $100\,\text{fb}$ are easily obtained but only for $m_1 + m_2 \lesssim m_Z$, where LEP bounds apply. For larger masses the cross section decreases very fast.

- If the electroweak moment interaction is strong enough to produce N_2-N_1 pairs, the N_2 will decay fast to $N_1\gamma$ (or $N_1 Z$ if allowed kinematically).
- The N_1 can only decay through mixing: either to fermion + weak boson, as in "pure" seesaw models, or to light neutrino + photon, through transition magnetic moments induced by the new interaction.
- The N_1 could possibly be rather long-lived, and might be spotted through a displaced decay vertex inside the detectors.
- Note, however, that predictions on the N_1 lifetimes depend on the mixing parameter ε, which is not model independent. For our calculations we assume seesaw with $M_R \sim 100\,\mathrm{GeV}$.

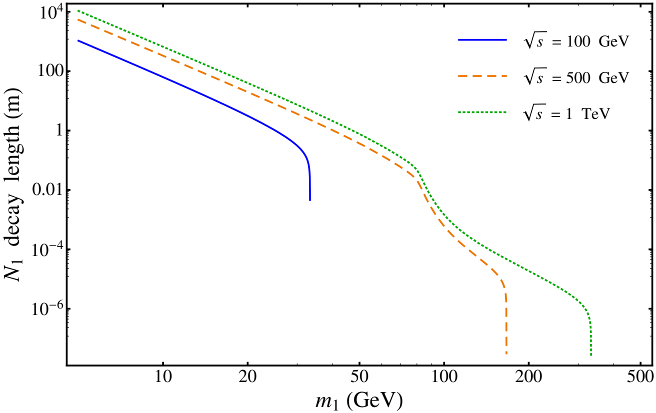
Branching Ratios for N_1

N_1 decay branching ratios for $\Lambda_{NP} = 10$ TeV

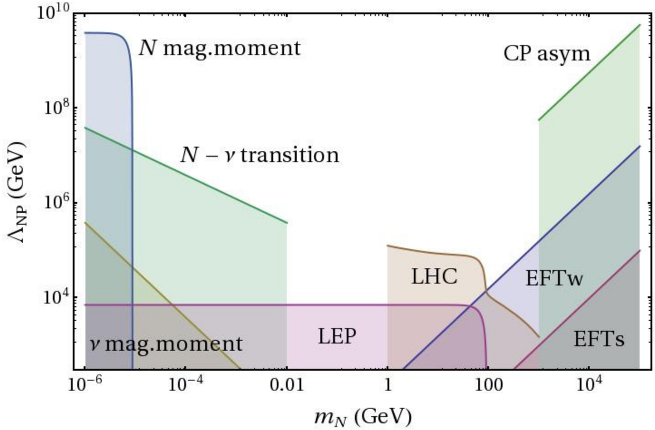


N_1 decay lengths

N_1 N_2 pair produced at CM ($m_2 = 2m_1$, $\Lambda_{NP} = 10\,\mathrm{TeV}, \varepsilon = 10^{-6}$)



Summary of Bounds and Prospects



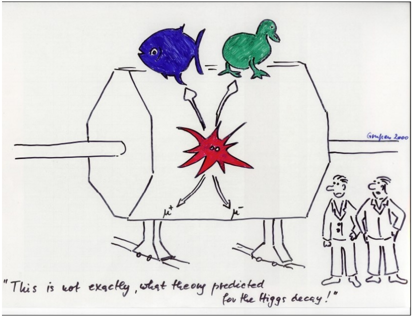
Conclusions

- Strong bounds from red giants cooling for $m_N \lesssim 10\,\mathrm{keV}$ ($\Lambda_{NP} > 4 \times 10^9\,\mathrm{GeV}$). In this case, negligible effects in collider experiments.
- For $10\,\mathrm{keV} \lesssim m_N \lesssim 10\,\mathrm{MeV}$ SN, $\gamma\nu \to N$, provides very strong bounds. However, they depend on ε.
- For $m_N \lesssim m_Z$, the invisible Z decays impose $\Lambda_{NP} \gtrsim 7 \times 10^3\,\mathrm{GeV}$, depending on the details of the heavy neutrino spectrum.
- For $m_N \sim 1\text{–}200\,\mathrm{GeV}$ and $7\,\mathrm{TeV} < \Lambda_{NP} < 100\,\mathrm{TeV}$, heavy neutrinos could be produced at the LHC with cross sections above $100\,\mathrm{fb}$. The heaviest will decay rapidly into hard photons. The lightest is quite long-lived and, in part of the parameter space, could produce non-pointing photons.

Outlook

- The magnetic coupling may have effects in the early universe because it can potentially alter the equilibrium conditions of the N and their decoupling temperature. Mandatory to compute relic abundances.
- Searches for hard photons in the Galaxy X-ray background could impose tight bounds on the new interactions.
- Heavy neutrinos with masses $\sim 1\,\mathrm{keV}$ could be a good dark matter candidate. The right-handed neutrino magnetic moments could change significantly the analysis of this possibility.
- One should evaluate carefully the effects of the Majorana magnetic couplings on non-thermal leptogenesis.
- For sufficiently large ζ, this same coupling might lead to the trapping of the right-handed neutrinos in the supernova core.

Thank you for your attention!



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